

Prepared in cooperation with the Arizona Department of Water Resources, Metropolitan Domestic Water Improvement District, City of Tucson, Town of Oro Valley, and Pima County

*The availability of ground water is of extreme importance in areas, such as southern Arizona, where it is the main supply for agricultural, industrial, or domestic purposes. Where ground-water use exceeds recharge, monitoring is critical for managing water supplies. Typically, monitoring has been done by measuring water levels in wells; however, this technique only partially describes ground-water conditions in a basin. A new application of geophysical technology is enabling U.S. Geological Survey (USGS) scientists to measure changes in the amount of water in an aquifer using a network of microgravity stations. This technique enables a direct measurement of ground-water depletion and recharge.*

*In Tucson, Arizona, residents have relied solely upon ground water for most of their needs since the 19th century. Water levels in some wells in the Tucson area have declined more than 200 ft in the past 50 years. Similar drops in water levels have occurred elsewhere in Arizona. In response to the overdrafting of ground water, the State of Arizona passed legislation designed to attain "safe yield," which is defined as a balance between ground-water withdrawals and annual recharge of aquifers. To monitor progress in complying with the legislation, ground-water withdrawals are measured and estimated, and annual recharge is estimated. The Tucson Basin and Avra Valley are two ground-water basins that form the Tucson Active Management Area (TAMA), which by State statute must attain "safe yield" by the year 2025.*



Gravity meter setup at a microgravity station.

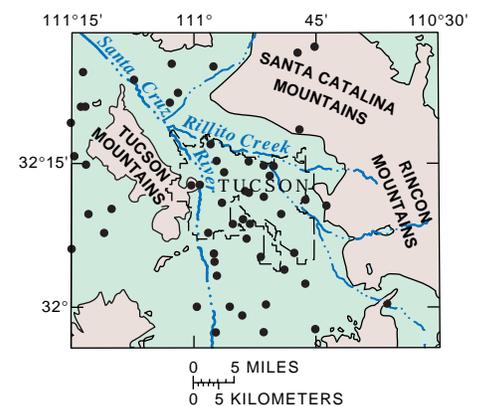
## Network of Microgravity Stations

Microgravity studies in the TAMA began in 1992 as part of a cooperative study by the USGS and the Pima County (Arizona) Department of Transportation and Flood Control District; 50 stations were established in a 6-square-mile area centered on Rillito Creek along the north edge of the city of Tucson. During the winter of 1992–93, unusually high precipitation occurred that was associated with El Niño (El Niño–Southern Oscillation), a warm water anomaly in the central to east equatorial Pacific Ocean. That wetter-than-normal winter caused ground-water recharge that provided the opportunity to demonstrate the use of microgravity to make detailed measurements of changes in water stored in aquifers. Late in 1997, the USGS established a network of about 60 microgravity stations within the TAMA to measure basinwide changes in ground-water storage. A return of El Niño in the winter of 1997–98 afforded another opportunity to use microgravity to measure the effects of such conditions on ground-water recharge in the basin.

Microgravity methods are based on the principles of Newton's Law of Gravitation that states that the

acceleration due to gravity within an object's gravitational field is directly related to the mass of the object and inversely related to the distance to the center of the object. In simple terms, the greater an object's mass, the stronger its gravitational field. Differences in measured gravitational fields over the earth's surface have been used by geophysicists for years to map variations in crustal thickness, the presence of magma bodies, and the subsurface distributions of different rock types.

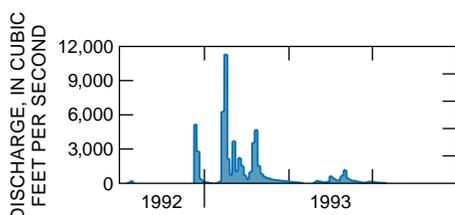
Ground water is stored within the pore spaces of aquifers. As an aquifer is drained by pumpage or filled by recharge, its mass changes, which results in changes in the strength of its gravitational field. Recent technological advances in geophysical techniques have made measurement of the extremely small gravitational changes caused by fluctuations of water volume practical. The standard unit of measurement for conventional gravity studies is the milligal, a unit equal to  $10^{-3}$  cm/sec<sup>2</sup>; microgravity work uses microgals, or  $10^{-6}$  cm/sec<sup>2</sup>. The USGS microgravity network is based on the University of Arizona network and is the first basinwide application of microgravity methods to the measurement of changes in ground-water storage.



Network of existing microgravity (aquifer-storage monitoring) stations in the Tucson Basin area.

## El Niño 1992–93, the First Measurements

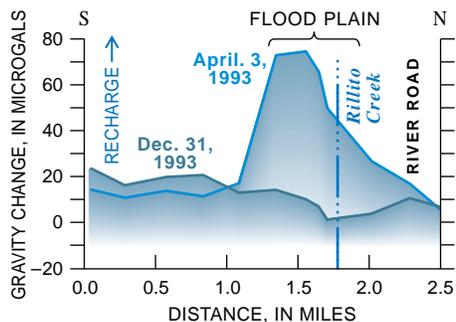
The usefulness of microgravity measurements for monitoring ground-water change was demonstrated in the winter of 1992–93 when El Niño conditions contributed to sustained, high streamflows throughout southern Arizona. Rillito Creek, which is normally dry, had substantial streamflow from December 1992 to March 1993. Infiltration of streamflow through channel sediments recharged the underlying aquifer, causing water levels and microgravity readings to rise. Repeated gravity measurements at 50 stations within the study area (12 stations along a 2.5-mile stretch of Swan Road) between December 1992 and January 1994 enabled scientists to calculate change in ground-water storage and to estimate recharge for each measurement period.



Discharge of Rillito Creek at Dodge Boulevard, December 1992–March 1993.

Microgravity studies showed that the greatest initial recharge occurred in normally unsaturated surficial deposits along Rillito Creek as a direct result of the winter streamflows. Throughout the winter of 1992–93, gravity values increased over a 0.5-mile-wide strip of flood plain adjacent to Rillito Creek and reached their maximum by April 1993. As water flowed away from the saturated, near-channel surficial deposits and dispersed through the aquifer, gravity values declined steadily nearest Rillito Creek. By January 1994, gravity values had returned almost to those measured at the start of the study. Throughout the area south of Rillito Creek, however, a residual gravity increase that correlated with rising water levels in wells indicated an increase in ground-water storage resulting from the previous winter's streamflows.

By integrating the values of gravity change over the network of microgravity stations, USGS scientists estimated that

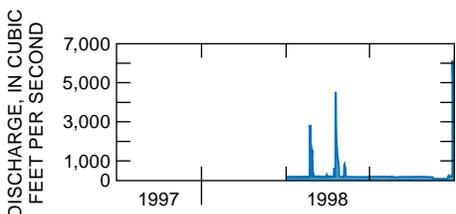


Gravity changes since December 1992 along Swan Road, April and December 1993.

about 10,900 acre-ft of recharge occurred along Rillito Creek during the winter of 1992–93, which was about 9 percent of the total streamflow recorded at the Dodge Boulevard streamflow-gaging station in that time (Pool and Schmidt, 1997).

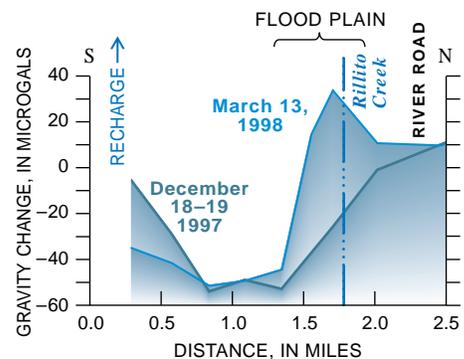
## El Niño 1997–98, Network in Place

In 1997, strong El Niño conditions returned to the Pacific Ocean increasing the possibility of higher-than-average precipitation in southern Arizona. In advance of the winter-storm season, microgravity stations in the network for the 1992–93 study were surveyed to establish new baseline-gravity levels. In addition, a basinwide network of about 60 microgravity stations was installed and surveyed. Widespread flooding did not occur in the winter of 1997–98 as the result of the El Niño, but normally dry washes flowed for days to weeks as the result of above-average precipitation. Although data collection has not been completed, a preliminary evaluation indicates that gravity changes adjacent to Rillito Creek were similar to changes in 1992–93. The same pattern of recharge was seen with the large bulge in gravity values at Rillito Creek caused by saturation of surficial deposits adjacent to the channel.

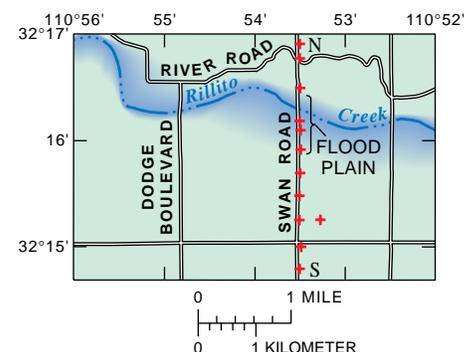


Discharge of Rillito Creek at Dodge Boulevard, December 1997–March 1998.

The use of synoptic microgravity measurements to determine changes in ground-water volume was demonstrated by its successful application to a site-specific area during the El Niño flooding of 1992–93. In 1997, application of the method was expanded in scale to a basinwide network that will be surveyed annually. The resultant data will enable water managers and scientists to monitor annual changes in ground-water conditions throughout the Tucson Basin and Avra Valley.



Gravity changes since December 1992 along Swan Road, December 1997 and March 1998.



Microgravity stations along Swan Road.

—J.T.C. Parker and D.R. Pool

## References Cited

Pool, D.R. and Schmidt, Werner, 1997, Measurement of ground-water storage change and specific yield using the temporal-gravity method near Rillito Creek, Tucson, Arizona: U.S. Geological Survey Water-Resources Investigations Report 97-4125, 30 p.

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